Study of Concrete Maturity Method in Very Cold Weather

Final Report

Prepared for

Alaska Department of Transportation & Public Facilities

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ABSTRACT

Maturity method can be used to estimate in-place strength of concrete during construction for administering timing of job control functions such as ending the curing period or cold-weather protection periods, opening to service, or removal of forms or false work. This report summarizes a comprehensive research program pertaining to the development of maturity protocols to facilitate in-place estimation of compressive strength for AKDOT concretes. This report is intended as a guide to AKDOT personnel for procedures and computations regarding the application of maturity method to AKDOT construction projects. Maturity constants, i.e. the datum temperature and the activation energy for the selected AKDOT concrete mix designs were determined through laboratory experiments. The strength-maturity relationships for the selected mix designs were established through cylinder testing. A construction project, Chena Hot Spring Road Retrofit in Fairbanks, Alaska was chosen for field studies. Two pier caps at two bridges of this project were instrumented with temperature sensors at the time of concrete placement. The thermal history and maturity inside the pier caps were recorded via electronic maturity meters. The strengths of the concrete estimated through the established strength-maturity correlation were interpreted and compared with the cylinder break strength. A guideline is proposed for estimating the early-age concrete strength by the maturity method in conjunction with the ASTM C1074 standard.

ACKNOWLEDGEMENTS

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SUMMARY

The maturity method is a technique to account for the combined effects of time and temperature on the strength gain of concrete by measuring the temperature of concrete during the curing period. The method provides a relatively simple approach for making reliable estimates of in-place strength at any particular age during construction. The main objective of this study is to produce a guide to procedures and computations regarding application of the maturity method to concrete construction projects in the State of Alaska and similar cold weather.

Laboratory experiments were conducted to determine the maturity constants of datum temperature and activation energy, to establish the strength-maturity correlations of typical AKDOT&PF concrete mix designs. Maturity index in terms of both temperature-time factor and equivalent age at a specified temperature were used, the best-fit correlation of the test data in terms of logarithmic and hyperbolic curves were proposed for the mix designs tested.

Field studies were performed on AKDOT&PF's Chena Hot Spring Road Retrofit project. At the project sites, the thermal history of the bridge pier caps were recorded via embedded thermocouples and converted into maturity values. The concrete strength in the structure was estimated in accordance to the measured maturity and the developed strength-maturity curve. The data was interpreted and compared with cylinder compressive testing results.

A protocol for implementation of maturity method in AKDOT projects was developed to be used in conjunction with ASTM C1074 "Standard Practice for Estimating Concrete Strength by the Maturity Method." The protocol summarizes the overall procedure for applying the maturity method to highway construction, describes the instrumentation and methods for making temperature measurements, performing maturity computations and predicting concrete strength.

This report begins with an introduction of the problem, objectives, and significance of the research in Chapter 1. Chapter 2 describes the procedure of maturity method according to the ASTM Standard C1074. The objectives and approaches of this investigation are followed in Chapter 3 and Chapter 4. Chapter 5 presents the results and analysis of the laboratory and field testing, including determination of maturity constants, development of strength-maturity correlation, and field estimate of concrete strength. Further discussions, conclusions and recommendations based on this study are included in the last chapter. A practice guideline, some relative testing data, and a spreadsheet showing the regression analysis of experimental data are available in the appendixes.

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1. INTRODUCTION

Economical cold-weather concreting requires the strength and quality of the concrete to determine when the formwork, heating and hoarding systems can be moved. Concrete's complex curing process, as influenced by both internal chemical action and external ambient conditions, prevents accurate prediction of strength gain by theoretical approaches. Conventional methods of measuring the concrete strength are through testing of cylinder or beam specimens often cast of the same batch of concrete in the project, cured under standard condition and then tested for the in-situ strength. These testing specimens under different curing conditions cannot fully reflect the early-strength gain associated with internal temperatures of the in-situ concrete structure and cannot accurately predict the strength of the major internal volume, particularly for thicker members.

The maturity method is a nondestructive testing approach for predicting the in-place strength of concrete. The rational behind the maturity method is that the strength development of concrete is correlated with its temperature in the early stages after pouring. The maturity of the concrete is a property of the hydration extent of the cementitious mixture. Two concrete samples of the same mix with the same maturity will have the same strength, even though each may have been exposed to different curing conditions. By embedding sensors in the concrete structure to measure the temperature history, concrete maturity technique uses a calibrated strength-maturity correlation curve based on the same concrete mix design to estimate the in-place concrete strength. The maturity testing process essentially consists of two steps: developing the maturity calibration curve and measuring the maturity of the in-place concrete. From this information, the strength of the in-place concrete can be monitored and assessed.

Both ASTM (C1074-04) and AASHTO (T325-04) have developed applicable standards for the testing of the maturity method (ASTM C1074, 2004; AASHTO T325, 2004). Based on field case studies conducted in several states (Ahmad et al. 2006, Dong et al. 2000, Luke et al. 2002, Tepke et al. 2004 and Tikalsky et at. 2003), it is clear that maturity method can predict concrete strengths. Over the years, use of the maturity method has increased as state highway agencies and industry have become more aware of the technology, and the equipment has become more advanced, ranging from simple thermometers placed in the concrete to microprocessor-controlled data-loggers, to wireless transmission of the data directly to construction staff, which can provide fast and accurate data of either temperature or maturity.

Adoption of maturity method can speed up concrete construction and increase safety. The benefits may include:

- identifying the earliest possible opening to construction traffic and public use
- allowing post-tensioning tendons to be stressed sooner.
- allowing forms to be stripped sooner and with more confidence that the operation is safe; rented forms can be returned sooner.
- in-place strength can be monitored at critical locations and in the youngest concrete.
- cold weather effects on strength gain can be monitored, and heating systems can be shut down sooner.
- some of the systems now available provide tamper-proof data to prove that the concrete gained the proper strength and wasn't subjected to unusually high or low temperatures.
- compressing the schedule can allow contractors to be paid sooner and reduce worker hours.
- the number of test cylinders or beams that must be made and tested is greatly reduced.
- low or high temperature (or too great a temperature gradient) can trigger an alert.

The Alaska Department of Transportation and Public Facilities has had limited experience with the maturity method. This research will develop a protocol for implementation of the maturity method to construction of (AKDOT&PF)'s concrete projects.

2 MATURITY METHOD PROCEDURE

The maturity method estimates the concrete strength at any particular age by measuring the temperature of concrete during its curing period. The temperature history is used to calculate a maturity index which increases with age and can be related to compressive strength by a strength-maturity curve. The maturity function often used in the United States to compute the maturity index is the Nurse-Saul equation (Nurse 1949), which is given as:

$$M(t) = \sum (T_a - T_0)\Delta t \tag{1}$$

Where,

$M(t) =$ Maturity index (^{o}C-hours or ^{o}C-days), or known as temperature-time factor (TTF),

Δt = Time interval (days or hours),

$T_a =$ Average concrete temperature during time interval, Δt, (^{o}C) and

$T_0 =$ Datum temperature, (^{o}C)

Another method in ASTM C1074 uses the equivalent age principle for the concrete maturity. The equivalent age is the age at a standard temperature that results in the same strength as under the nonstandard condition. In the equivalent age approach, the maturity function, also known as the Arrhenius equation, is based on the rate of the chemical reaction in the concrete (Freiesleben and Pedersen 1977):

$$t_e = \sum e^{-Q\left(\frac{1}{273+T_a} - \frac{1}{273+T_s}\right)} \Delta t \tag{2}$$

Where,

$t_e =$ Equivalent age at a specified temperature, T_s (days or hours),

$Q =$ Apparent activation energy, or activation energy divided by universal gas constant (8.3144 J/(mol·K)) (^{o}K),

$T_a =$ Average concrete temperature during time interval, Δt (^{o}C),

$T_s =$ Specified temperature (^{o}C) and

Δt = Time interval (days or hours).

ASTM C1074 permits either temperature-time factor (TTF) or equivalent age to be used for the concrete maturity method. Nevertheless, the TTF maturity methodology is more widely used by state highway agencies, largely because of its simplicity. The equivalent age may be interpreted as the number of days or hours at a specified temperature required to produce a maturity value equal to the value achieved by a curing period at temperatures different from the specified temperature.

The maturity testing process essentially consists of two steps (Figure 1): developing the maturity calibration curve and measuring the maturity of the in-place concrete. The strength versus maturity (either TTF or equivalent age) relationships established in the laboratory are used in the field. Field thermal history data is converted to TTF or equivalent age, which is then employed in the strength-maturity relationship to determine the strength of in-place concrete at the specified ages.

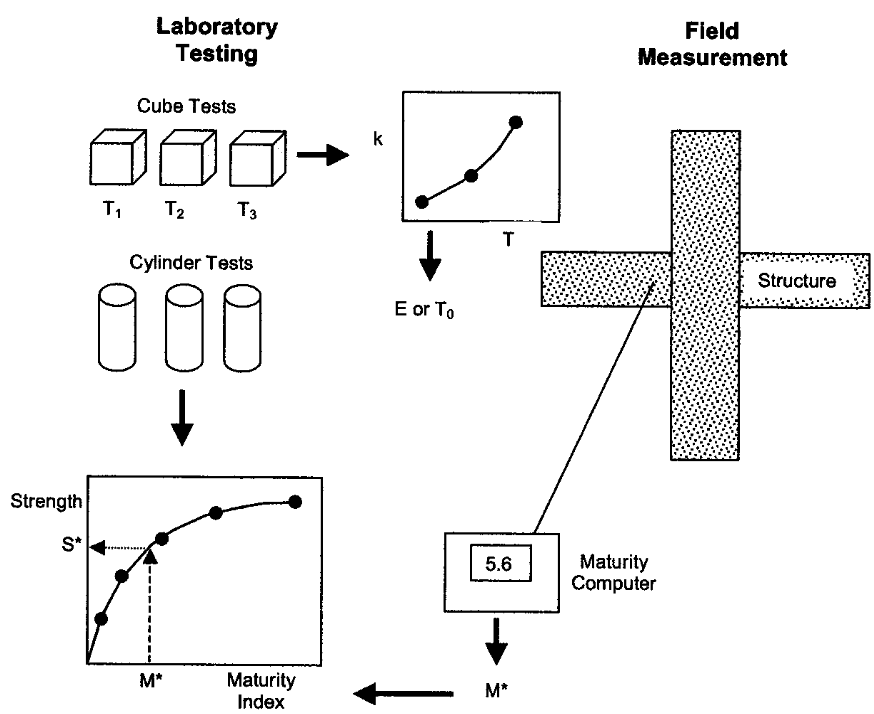


Figure 1 Maturity testing process (Carino and Lew, 2001)

In this study, both TTF method and equivalent age method were used and compared. In the equivalent age method, the specified temperature was taken as 296.15 K (23 ^{o}C). The main maturity parameter involved in calculating TTF and equivalent age is the datum temperature, T_0 and activation energy. The datum temperature is defined as the lowest temperature above which concrete can develop its strength, below which the concrete strength gain will cease. Approximate value of datum temperature is given in ASTM C1074 as 0 ^{o}C for Type I cement without admixtures and a curing temperature range from 0 to 40 ^{o}C. The exact temperature at which strength gain ceases for each concrete mix depends on its composition and the properties of the cementitious materials and chemical admixtures used. Therefore, more accurate strength predictions are achieved if these parameters are evaluated for specific cement brands and types, as well as the admixture types employed in the mixture.

3 STUDY OBJECTIVES

Though the concept of the maturity method has been known for decades, it is not used routinely in most states. Alaska DOT has very limited experience with this method. The objectives of this study are to develop laboratory and field testing protocols for the use of the maturity concept in AKDOT&PF's concrete projects. This research will also provide practice guidelines for using the maturity method in cold weather concreting.

4. RESEARCH APPROACH

This study encompasses a rigorous experimental program pertaining to the ASTM C1074 standards. As it will be explained in later sections of this report, typical AKDOT&PF concrete mixtures were prepared in the laboratory to measure the datum temperatures and the activation energy for maturity index calculation and to develop the strength-maturity correlation for field implementation.

Field and laboratory maturity computations and data acquisition processes were automated to facilitate establishing real-time temperature-age data, and strength-maturity correlation relationships. For this purpose, thermocouple wires were selected as the temperature sensors and were embedded in fresh concrete, and connected to a multi-channel Humboldt system. The Humboldt system serves as both the data logger and the reader which can record data of up to 4 maturity sensors. The system operates with a rechargeable internal battery and the thermocouple wires get the necessary power supply from the battery source.

The investigation was conducted in three phases:

1) Literature review and selection of AKDOT concrete mix designs for maturity testing.

2) Laboratory testing including determination of maturity constants and development of strength-maturity correlation curves for the selected mixes.

3) Field testing of maturity method in a selected AKDOT concrete project. This phase includes instrumentation of the in-place concrete with temperature sensors; measurement of the maturity and estimate of the in-situ concrete strength; and results analysis.

5 RESULTS AND ANALYSIS

Since the field demonstration was going to choose a construction project in the Fairbanks area, six concrete mix designs most commonly used in this area for AKDOT Class A and Class AA concrete were tested in the laboratory to measure the maturity parameters of datum temperature and activation energy, and to develop the strength-maturity correlations. The mix designs provided by AKDOT are attached in Appendix A. As could be seen later in this section, the Chena Hot Spring Road Retrofit project near Fairbanks was selected and the maturity method was implemented to the concrete construction in the bridge pier caps of the project.

5.1 Determination of Datum Temperature and Activation Energy

The testing required for experimental determination of datum temperature and activation energy was performed with mortar specimens, and results are applicable to concrete made with the same mortar composition. The basic steps, as described in ASTM C1074, are

1) Cast three sets of mortar cubes of similar proportion to the mortar of the field concrete and cure in water baths controlled at the maximum, minimum and the midway between the two extreme temperatures expected in the in-place field concrete in Fairbanks area during the time the strength predictions will be made. The three bath temperatures were 40 ^oF (4.4 ^oC), 60 ^oF (15.6 ^oC), and 80 ^oF (26.7 ^oC).

2) For each set of cubes, determine the compressive strength of three cubes in accordance with Test Method C109 at specified ages.

3) For each curing temperature, plot the average strength gain versus time and fit the data with the following function

$$S = S_u \frac{K(t-t_0)}{1+K(t-t_0)} \qquad (3)$$

where:

S = average cube compressive strength at age t (a variable),

t = test age (a variable),

S_u = limiting strength (a regression coefficient),

t_0 = age when strength development begins (a regression coefficient), and

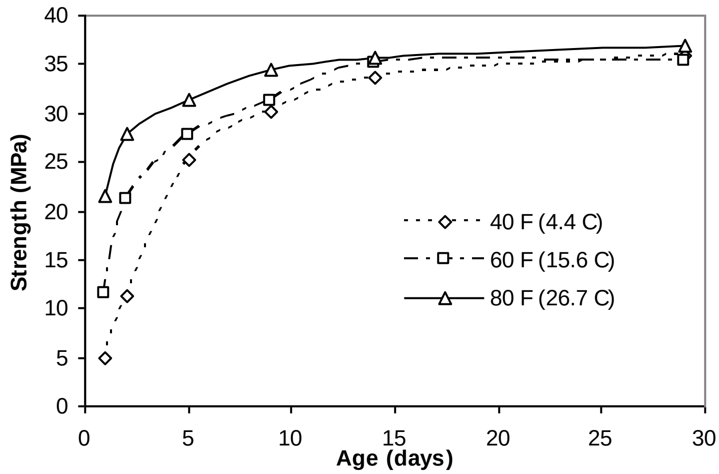
K = the rate constant (a regression coefficient).

This regression analysis could be conducted by a spreadsheet program similar to the program shown in Appendix B.

4) Plot the rate constants (K-values) as a function of the water bath temperature. Determine the best-fitting straight line through the three points and determine the intercept of the line with the temperature axis. This intercept is the datum temperature T_0 which is used in computing TTF according to Eq 1.

5) Plot the natural logarithms of the K-values vs. the reciprocal of the absolute temperatures (in kelvin) of the water baths. Determine the best-fitting straight line through the three points. The negative of the slope of the line is the value of the activation energy divided by the gas constant, Q which is used in computing equivalent age according to Eq 2.

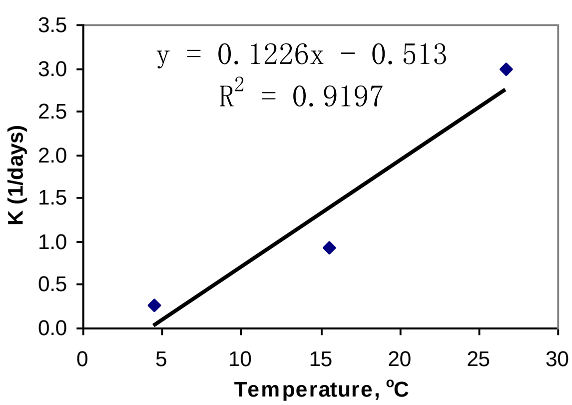
The results of cube testing are shown in Figure 2 to Figure7. A summary of the datum temperatures and activation energy for the tested six concrete mixtures is listed in Table 1.



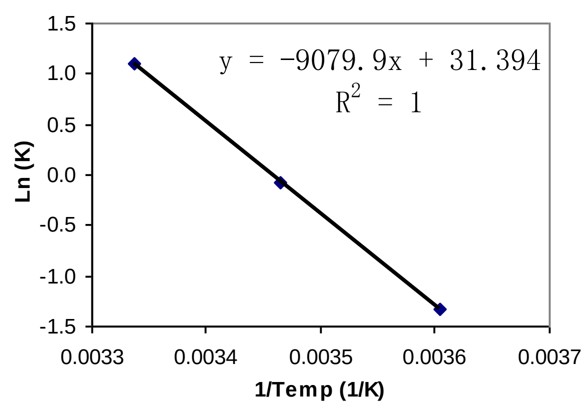
(a) Cube strength vs. age

(b) Regression analysis of Eq 3

T (^oC)	K (1/day)	t_0 (day)	S_u (MPa)
4.44	0.264	0.5	42.553
15.56	0.930	0.5	35.971
26.67	2.989	0.5	35.587

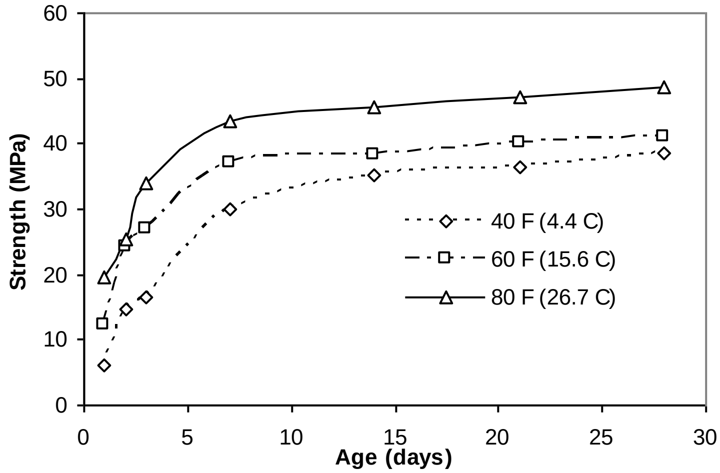


(c) Determination of datum temperature



(d) Determination of activation energy

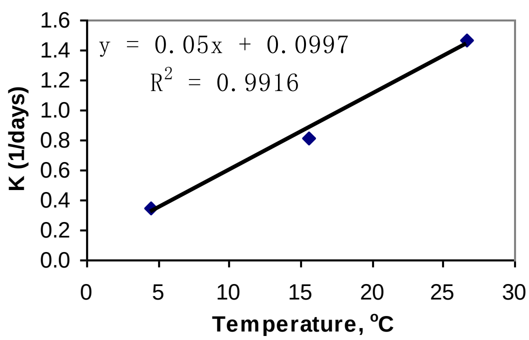
Figure 2 Cube test results of University Redi Mix # 34401A



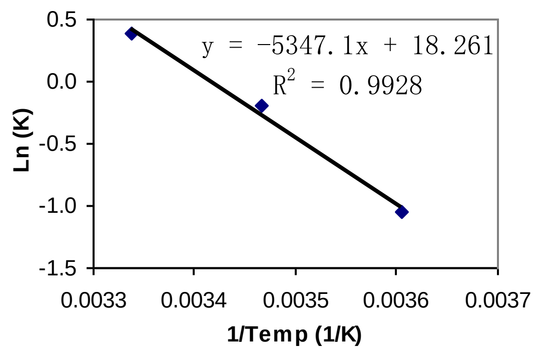
(a) Cube strength vs. age

(b) Regression analysis of Eq 3

T (^oC)	K (1/day)	t_0 (day)	S_u (MPa)
4.44	0.351	0.5	40.650
15.56	0.819	0.5	42.373
26.67	1.464	0.5	44.643

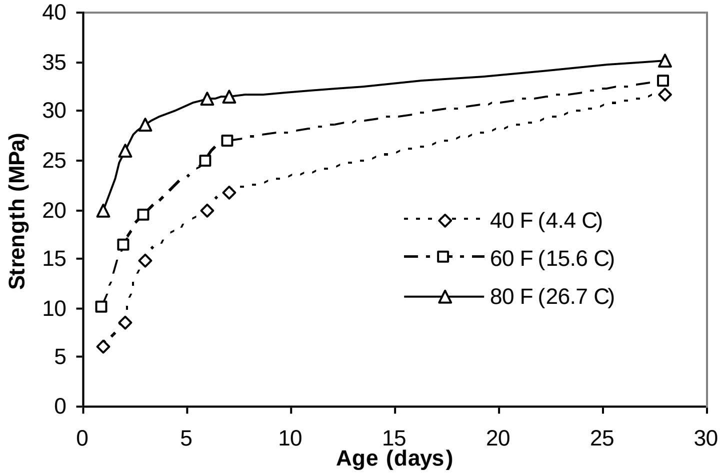


(c) Determination of datum temperature



(d) Determination of activation energy

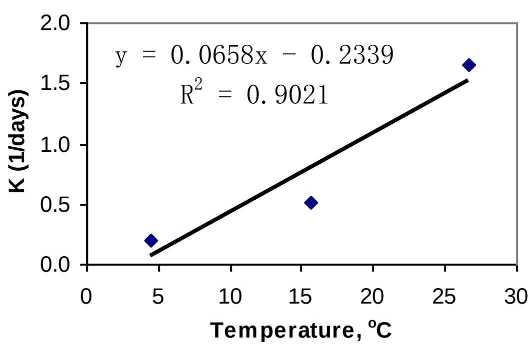
Figure 3 Cube test results of University Redi Mix # 34501AA



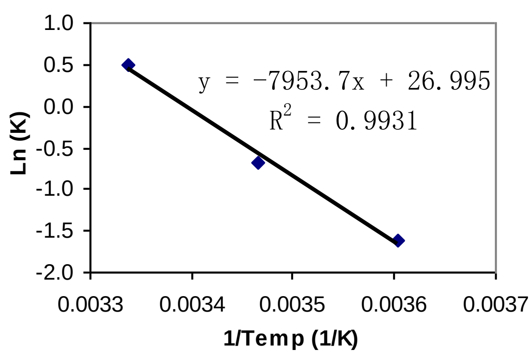
(a) Cube strength vs. age

(b) Regression analysis of Eq 3

T (^{o}C)	K (1/day)	t_0 (day)	S_u (MPa)
4.44	0.197	0.01	35.971
15.56	0.511	0.2	33.784
26.67	1.659	0.2	34.843

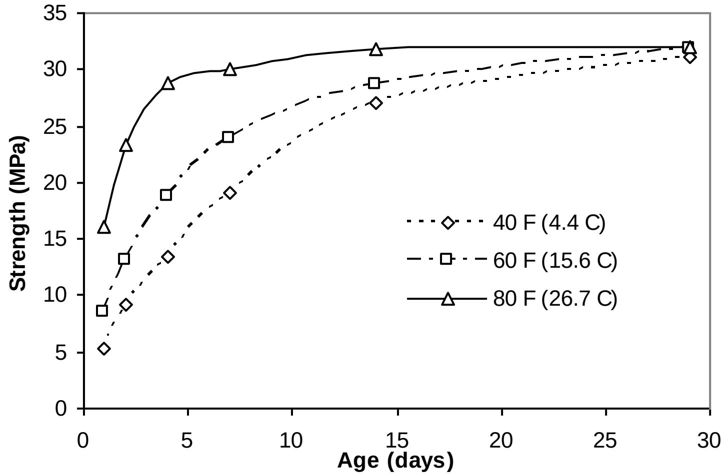


(c) Determination of datum temperature



(d) Determination of activation energy

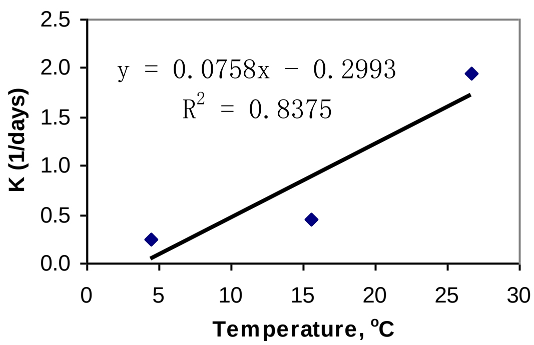
Figure 4 Cube test results of Fairbanks Sand & Gravel Mix # 1601

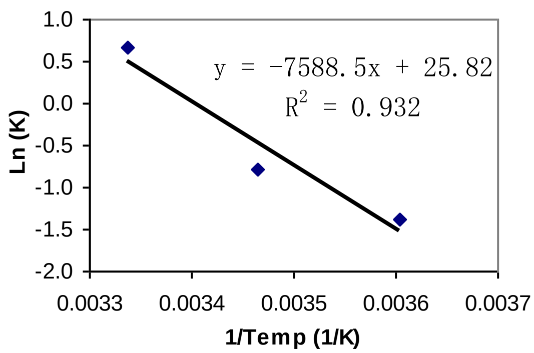


(a) Cube strength vs. age

(b) Regression analysis of Eq 3

T (^{o}C)	K (1/day)	t_0 (day)	S_u (MPa)
4.44	0.252	0.2	30.675
15.56	0.452	0.2	31.348
26.67	1.937	0.5	32.468

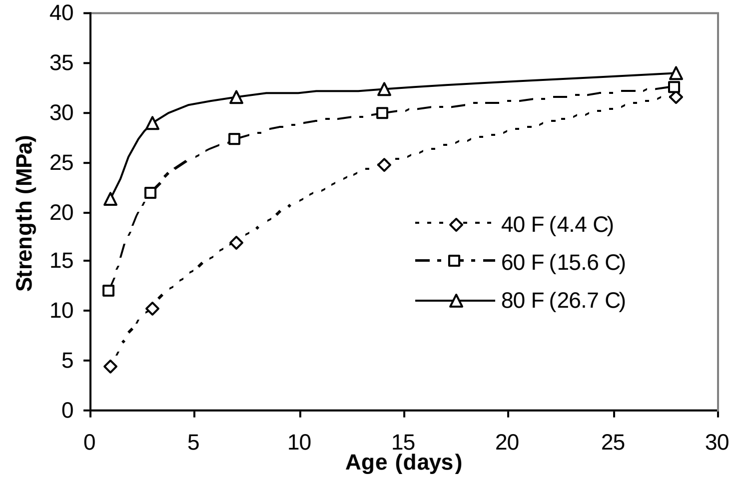




(c) Determination of datum temperature

(d) Determination of activation energy

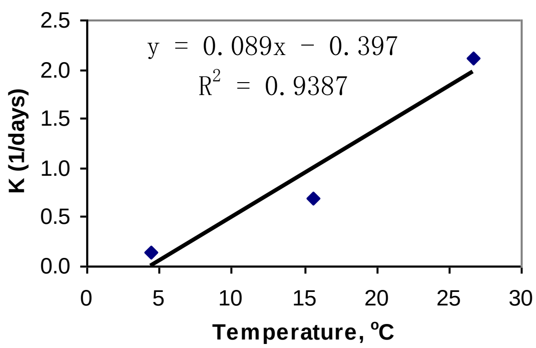
Figure 5 Cube test results of Fairbanks Sand & Gravel Mix # 1551



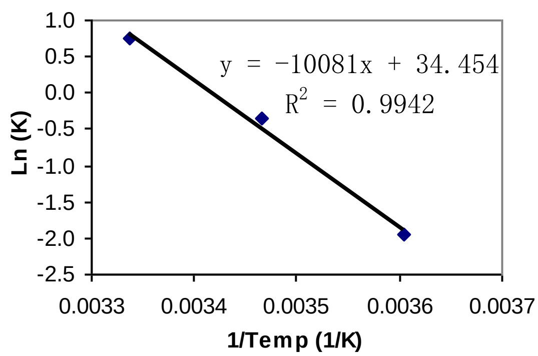
(a) Cube strength vs. age

(b) Regression analysis of Eq 3

T (^oC)	K (1/day)	t_0 (day)	S_u (MPa)
4.44	0.144	0.01	35.461
15.56	0.696	0.2	33.113
26.67	2.122	0.2	33.898

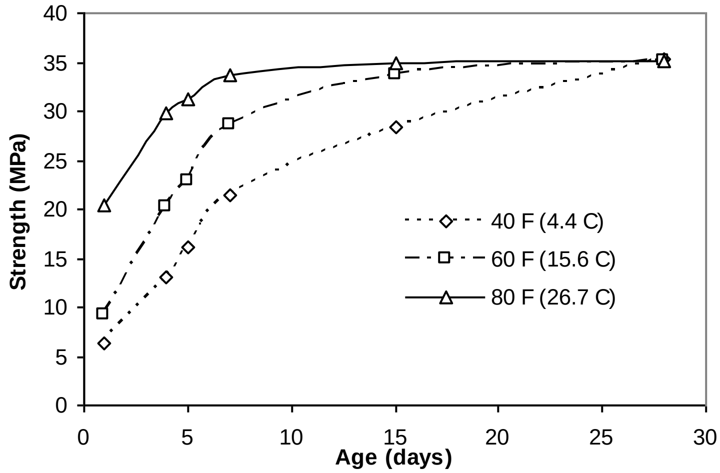


(c) Determination of datum temperature



(d) Determination of activation energy

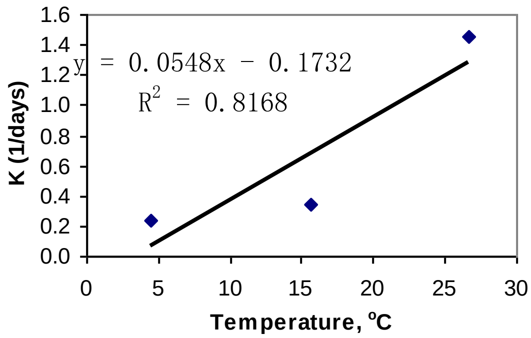
Figure 6 Cube test results of H. C. Redi Mix # 60341



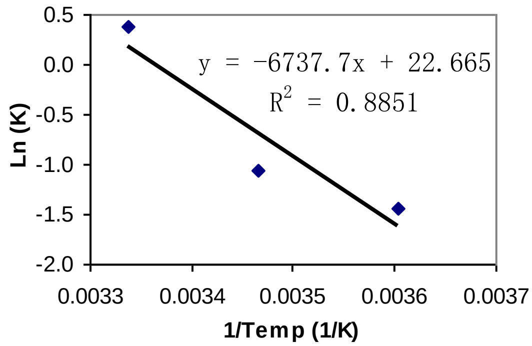
(a) Cube strength vs. age

(b) Regression analysis of Eq 3

T (^oC)	K (1/day)	t_0 (day)	S_u (MPa)
4.44	0.237	0.01	32.468
15.56	0.347	0.1	38.023
26.67	1.455	0.1	35.971



(c) Determination of datum temperature



(d) Determination of activation energy

Figure 7 Cube test results of H. C. Redi Mix # 65341

Table 1 Datum temperatures and activation energy

Concrete Mix Designs		Datum Temperature, T_0 (^oC)	Apparent Activation Energy, Q (^oK)
University Redi Mix	#34401A	4.2	9080
	#34501AA	-2.0	5347
Fairbanks Sand & Gravel	#1601	3.6	7954
	#1551	3.9	7588
H. C. Redi Mix	#60341	4.5	10081
	#65341	3.2	6738

Note: Apparent activation energy is activation energy divided by the gas constant

5.2 Development of Strength-Maturity Relationship

The procedure described below is based on the ASTM C1074 requirements for laboratory establishment of strength-maturity correlation of the concrete to be placed in the field.

1) Prepare at least 15 cylinder specimens according to ASTM C192 for each concrete mix using the mixture proportions and constituents, including admixtures, of the concrete whose strength-maturity relationship is to be developed.

2) Embed one temperature sensor (general a thermocouple) into each of at least two cylinder specimens at approximately half-height through the top of the cylinders. Record the temperature at a time interval of half hour or less for the first 48 hours of the temperature. Larger time intervals may be used for the relatively constant portion of the subsequent temperature record.

3) Cure the specimens in a water bath or in a moist curing room, meeting the requirements of specification ASTM C511.

4) Perform compression tests of at least three specimens at the ages of 1, 3, 7, 14 and 28 days, in accordance with test methods ASTM C39.

5) At each test age, calculate and record the average maturity value for the instrumented specimens in terms of TTF (Eq 1) or equivalent age (Eq 2).

6) Create a spreadsheet to plot the average compressive strength as a function of the average maturity value. Draw a best-fit curve through nonlinear regression analysis of the data.

The correlation curve equation should be based on any function that accurately describes the data. Two of the most common relationships are the logarithmic and hyperbolic functions. The form of the logarithmic function is:

$$S = A + B \ln(M) \tag{4}$$

where:

S = estimated strength of the concrete at a given maturity (a variable),

A, B = regression constants,

M = maturity index (a variable).

The form of the hyperbolic function is as follows (Carino 1981):

$$S = S_u \frac{K(M - M_0)}{1 + K(M - M_0)} \tag{5}$$

where:

S = estimated strength of the concrete at a given maturity (a variable),

S_u = regression constant analogous to the ultimate strength that the concrete will attain,

M = maturity index (a variable),

M_o = regression constant analogous to the maturity when strength gain begins,

K = regression constant analogous to a rate constant.

The logarithm trendline function is available in all spreadsheet programs and hence can be easily obtained. A program that can generate the hyperbolic function in Equation (5) for inputted data and determine the regression constants is attached in Appendix B.

For each mix design, the maturity index of TTF at the age of cylinder testing was calculated or recorded from the maturity meter based on the temperature history. The strength versus maturity (TTF) data and the correlation curves of both logarithm and hyperbola for the six mix designs of AKDOT concrete are shown in Figure 8 to Figure 13. In general, both the logarithmic and hyperbolic curves adequately fit the data, but the hyperbolic curve fits better as shown by the R-squared values. In practice, the logarithmic correlation is popular because of its simplicity even though it doesn't provide a good representation of the relationship between strength and maturity for low or high maturity index. These strength-maturity relationships are to be used for estimating the strength of concrete mixture cured under other temperature conditions, such as those in the structure.

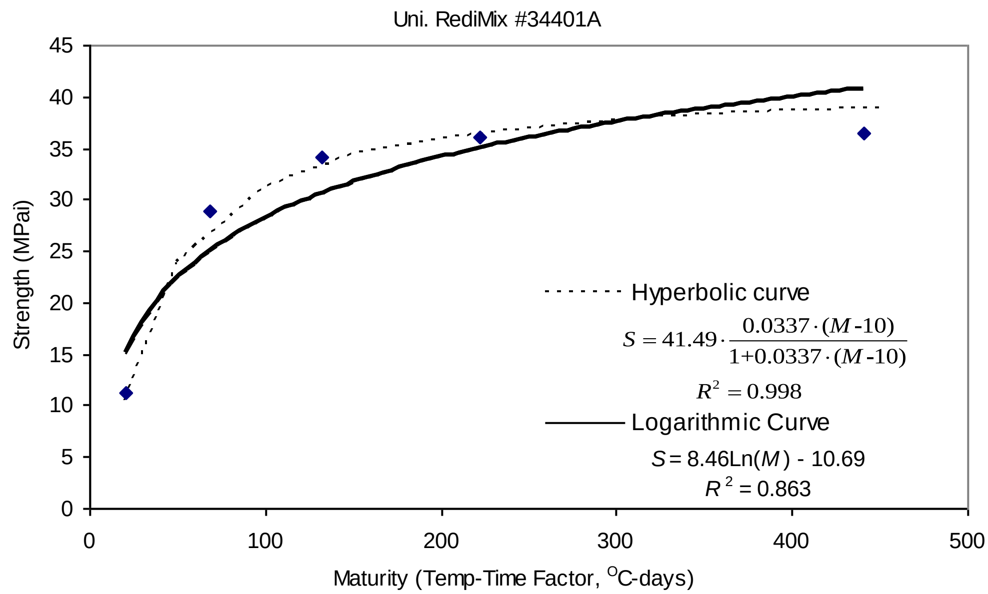


Figure 8 Strength-maturity correlation curve of University Redi Mix # 34401A

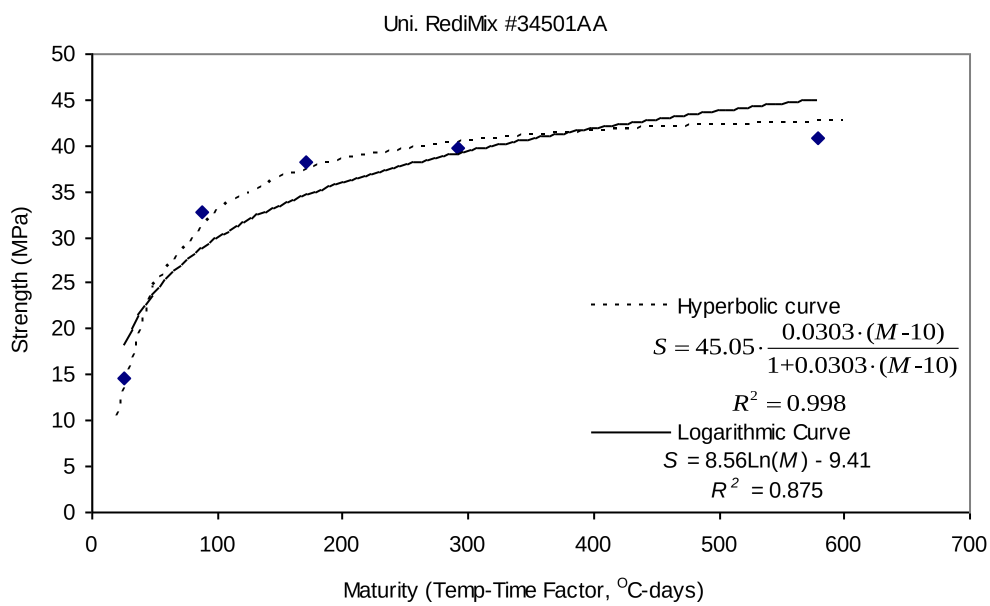


Figure 9 Strength-maturity correlation curve of University Redi Mix # 34501AA

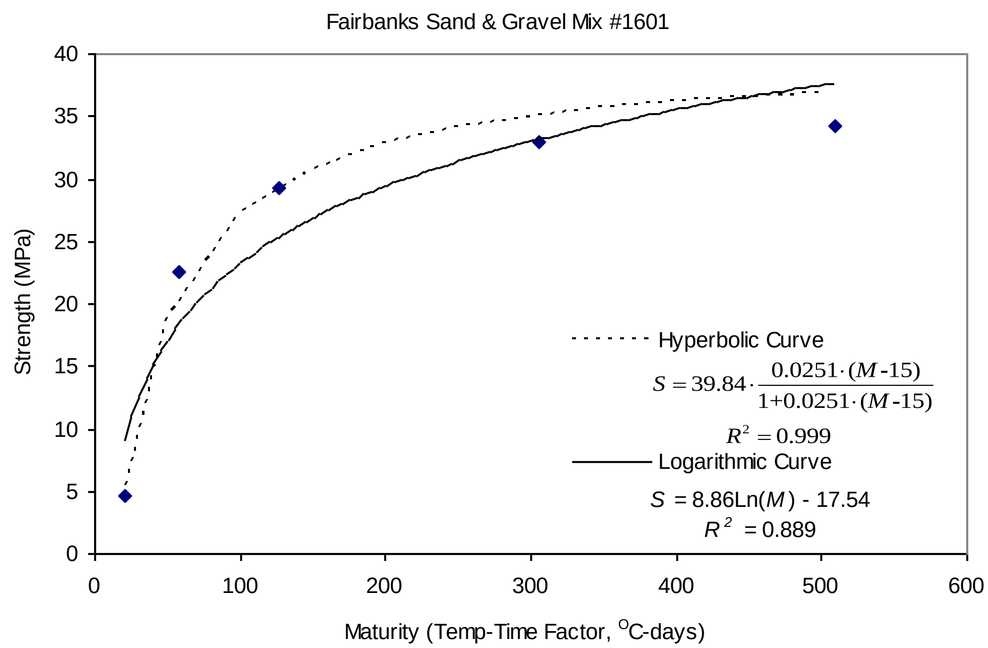


Figure 10 Strength-maturity correlation curve of Fairbanks Sand & Gravel Mix # 1601

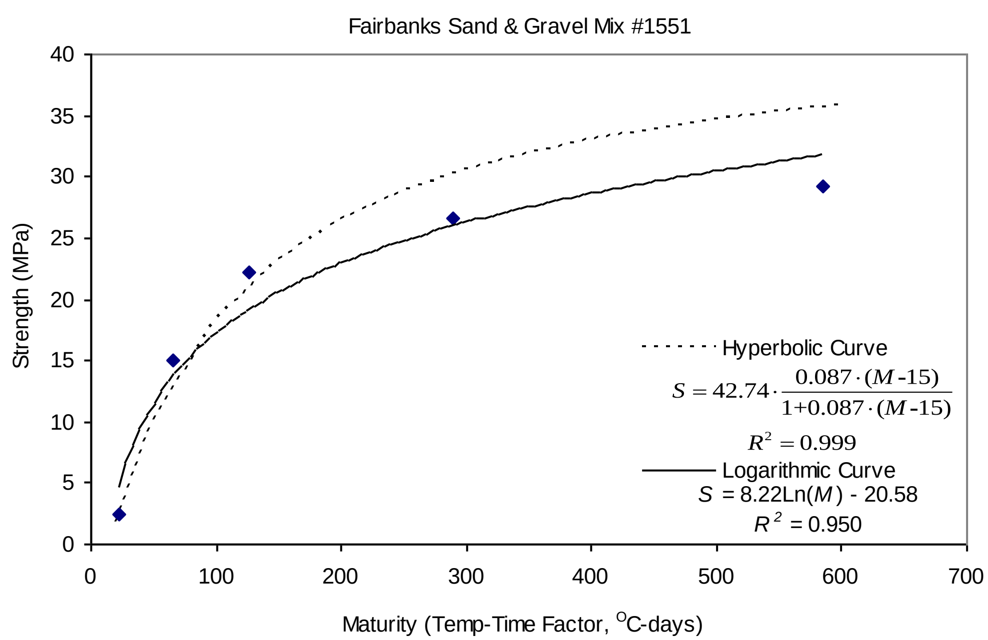
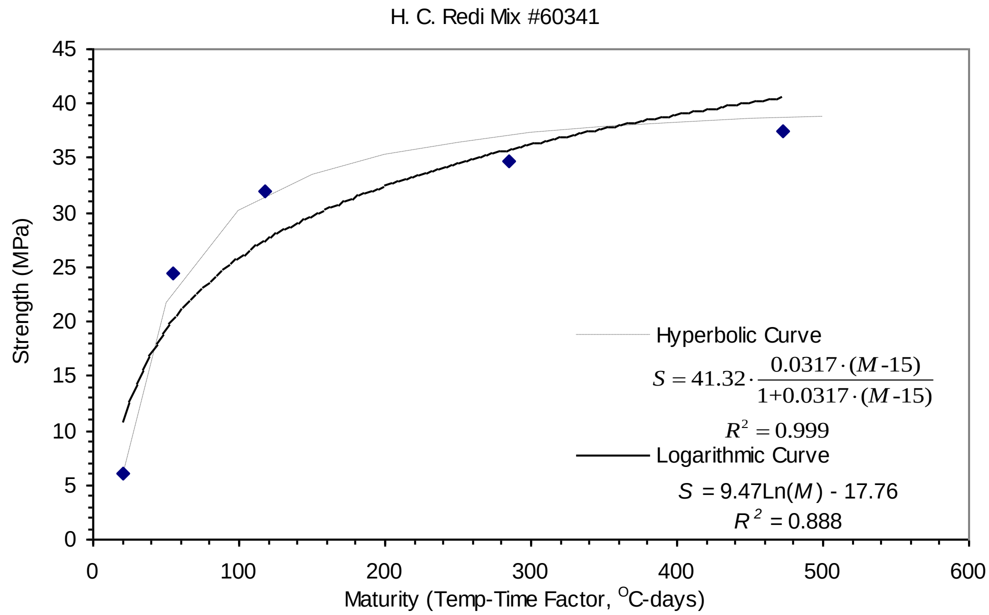
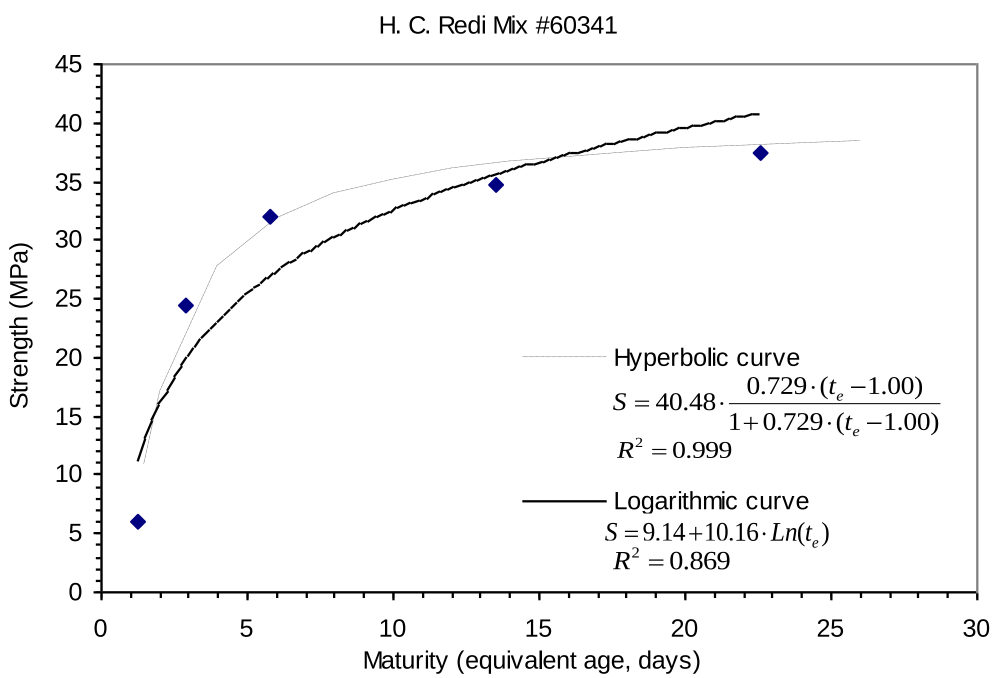


Figure 11 Strength-maturity correlation curve of Fairbanks Sand & Gravel Mix # 1551



(a) Temperature-time factor



(b) Equivalent age at temperature of 23 °C

Figure 12 Strength-maturity correlation curve of H. C. Redi Mix # 60341

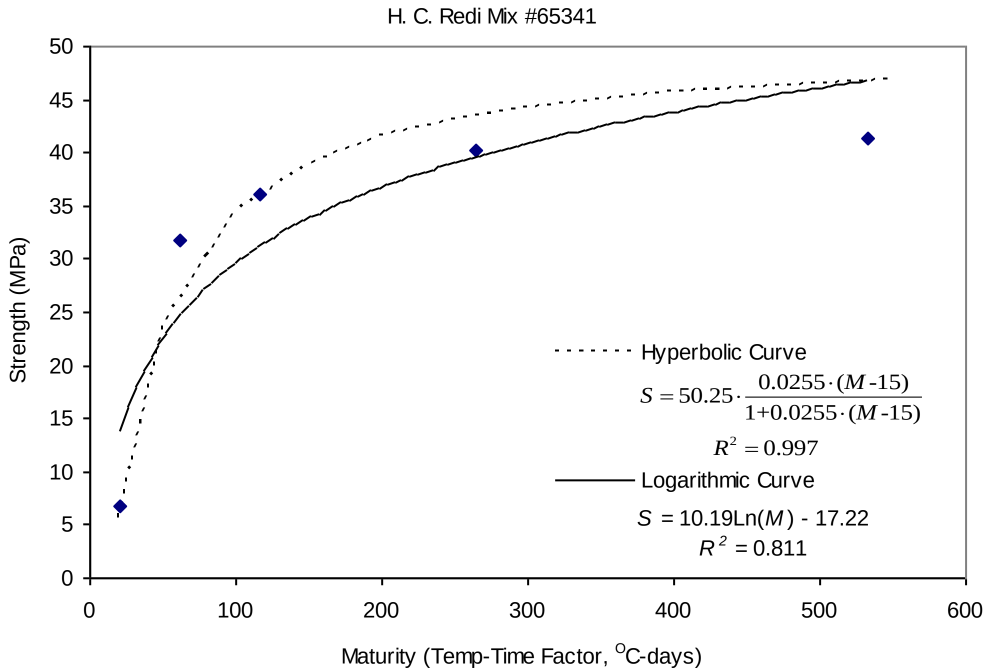


Figure 13 Strength-maturity correlation curve of H. C. Redi Mix # 65341

All the above strength-maturity relationships are developed only on the temperature-time factor except in mix design of H. C. Redi Mix # 60341. As it was shown later in this report, this mix design was used for the selected field project. Therefore, the strength-maturity correlations in terms of both temperature-time factor and equivalent age were established. Since the temperature data and the maturity parameter of activation energy are already available, this was not a lot extra work. Whether to use the temperature-time factor (TTF) or equivalent age for the maturity index, the correlation curves of H. C. Redi Mix # 60341 don't show much difference (Figure 12). For a specific mixture, both TTF and equivalent age may need to be calculated based on the temperature history, the one predicts the strength better should be used in the maturity method for estimation of early concrete strength.

5.3 Field Implementation

To estimate the concrete strength in a construction project using the maturity method, the following general steps should be taken:

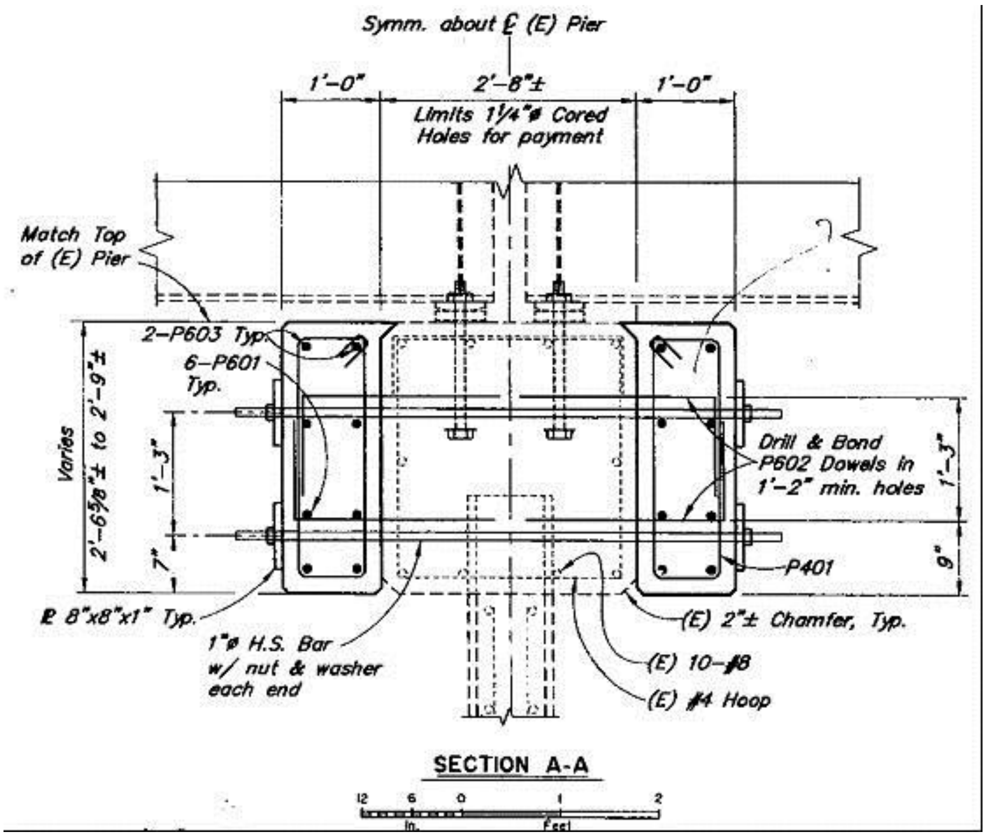
1) Plan and install the temperature sensors (thermocouples) prior to concrete placement. The sensors should be placed at critical locations where the concrete strength is required

2) Begin recording temperature data as soon as possible after concrete placement.

3) Use the temperature data to calculate the maturity index in terms of Temperature-Time Factor or Equivalent Age during aging. A maturity meter can be used to record the temperature and the maturity at the same time.

4) From the correlation equation, estimate the concrete strength from the calculated maturity at the specified ages. Alternatively, use the correlation equation to determine the maturity of the concrete at a desired strength level and monitor the maturity until that level is achieved.

The field implementation in this study was to verify the maturity method by comparison with the cylinder testing and to establish a protocol for future applications of the maturity method in Alaska. AKDOT's Chena Hot Spring Road Seismic Retrofit project was selected for the maturity method demonstration. In this project, the existing bridge pier caps were retrofitted as shown in Figure 14. The temperature and maturity development in the new concrete was going to be measured; the strength gain in the new concrete would be estimated and compared with cylinder testing results to help the contractor in performing post tensioning.



(a) Typical section of bridge pier cap retrofit

(b) Concrete placement

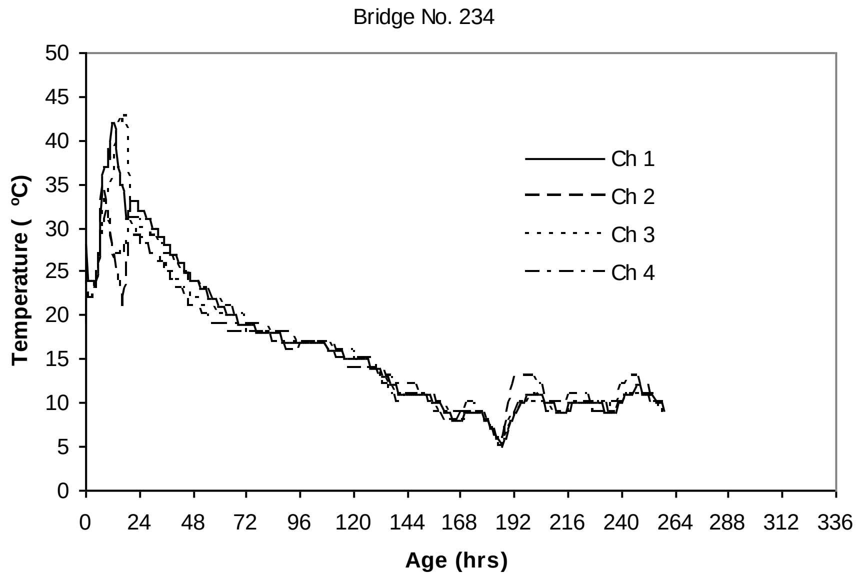
Figure 14 Bridge pier cap retrofit

(a) Thermocouples tied to rebars (b) Maturity meter

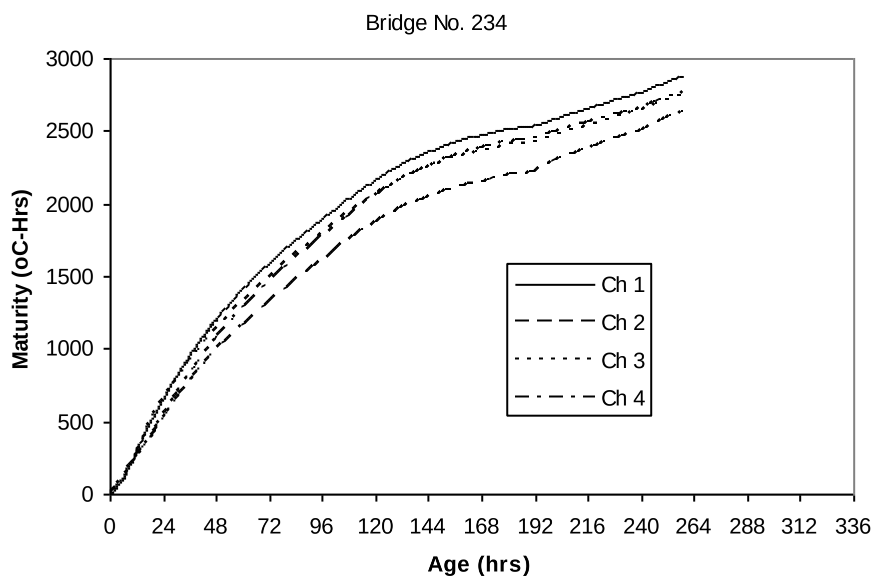
Figure 15 Concrete maturity measurement

The concrete used for the bridge pier cap was H. C. Redi Mix #60341. Because the access to the bridge pier cap depends on the scaffolding of the contractor, one pier at each of Bridge No. 234 and Bridge No. 237 was selected to be instrumented with temperature sensors for maturity testing according to the construction schedule. The temperature in the center of the structure usually is higher than at the sides. Since the sensors had to be attached to rebars, four thermocouples were fastened to the top and bottom dowel reinforcements to avoid the sensor being on the stirrups which are too close to the formed sides (Figure 15) at each pier. Two of the four sensors were located at near end of the cap and the other two at one third of the cap span. The thermocouple wires were not in direct contact with the reinforcing steel or formwork, and were carefully led out of the formwork to a Humboldt 4101 maturity meter to protect them from damage during concrete placement. Before the placement of concrete, a test was conducted to make sure that all the sensors were in working condition. After the concrete was placed, the maturity meter was activated and collected temperature data for about ten days because the contractor removed the scaffolding after post-tensioning and further later access to the maturity system would be impossible.

The recorded temperature and maturity development in the two bridge pier caps are shown in Figure 16 and Figure 17.



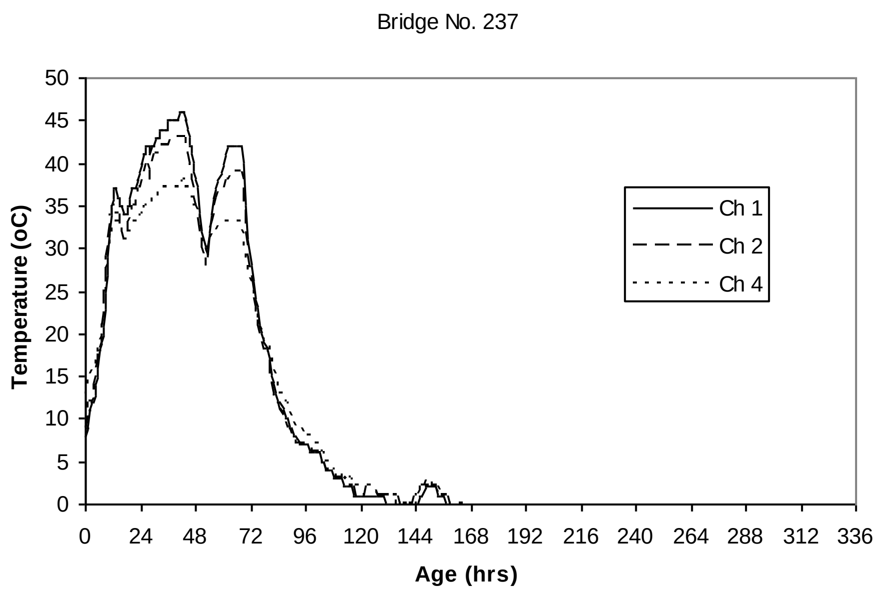
(a) Temperature development



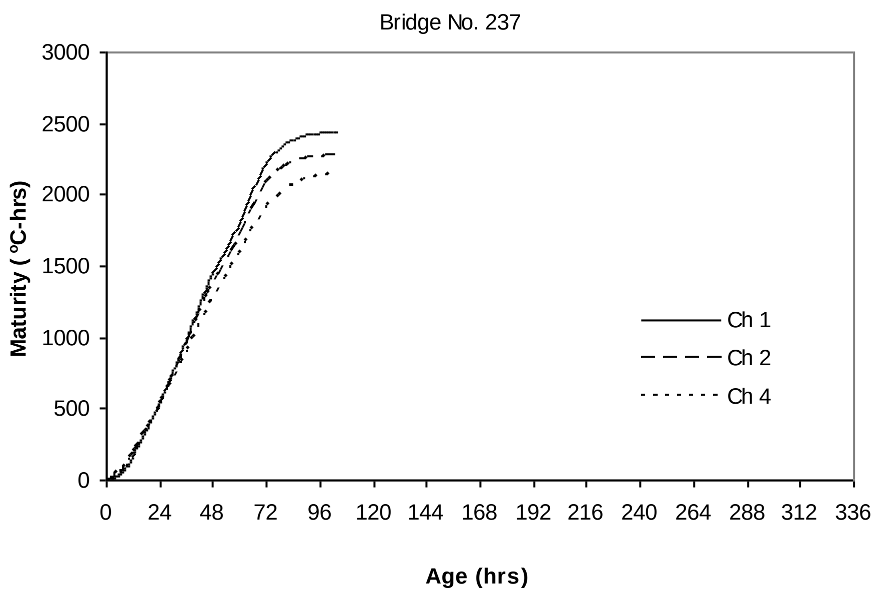
(b) Maturity development

Figure 16 Field measurements at Bridge No. 234

(Concrete poured on Aug 04, 2009)



(a) Temperature development



(b) Maturity development

Figure 17 Field measurements at Bridge No. 237

(Concrete poured on Oct 03, 2009)

Maturity Development in the Structures

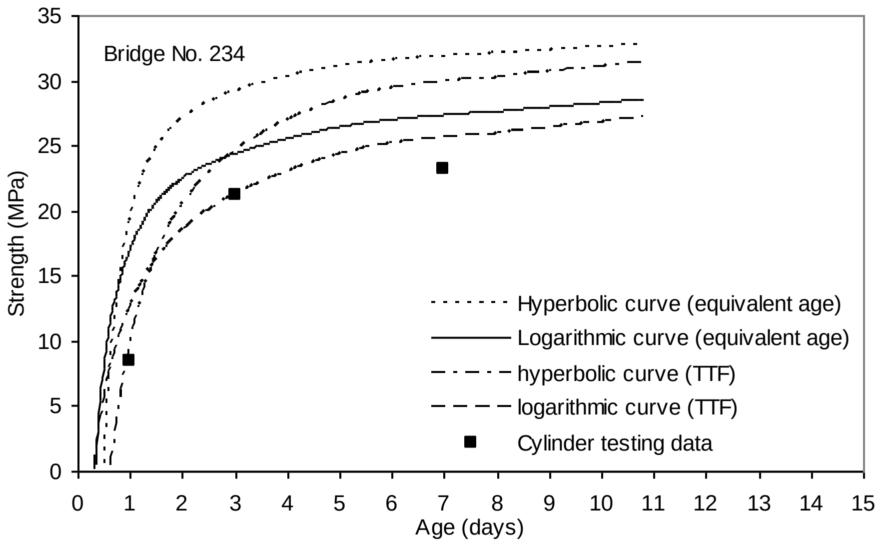
The temperature and maturity development were similar at the four locations in the piers, therefore the average value of the different locations would be used. Although precautions were taken, one thermocouple in the second pier cap was damaged and did not record any temperature data. It was believed the damage was caused during vibration of the concrete. With the datum temperature, T_0 and activation energy, Q as the input parameters, the maturity meter can compute and record both temperature and maturity indices of TTF and equivalent age.

For Bridge No. 234, the concrete was poured on August 4th when the weather was warm. As predicted, the temperature profile indicates a peak during the first 24 hours and then there was a gradual drop. The maturity developed on the other hand was faster in the first 48 hours and then gradually slowed down (See Figure 16).

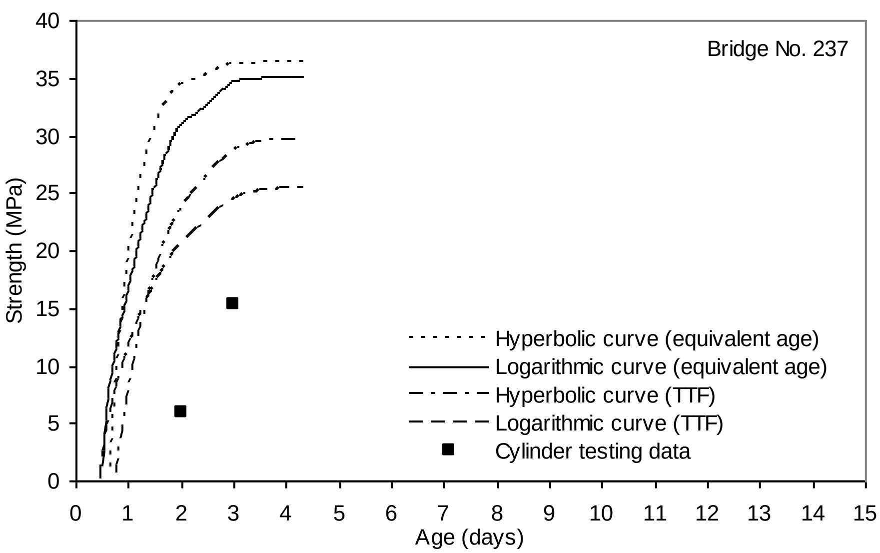
For Bridge No. 237, the concrete was poured on October 3rd when the weather was already very cold on the project site and heating was used during the curing to keep the concrete warm. The recorded data showed the dramatic temperature drop after the heating was terminated after three days. After day 4, the recorded temperature was below the datum temperature for this concrete and the contribution the maturity increase was neglected (See Figure 17).

Estimate of Concrete Strength

In this project, the contractor was expecting the time when the concrete gained 80% of design strength for conducting post-tensioning. As the conventional practice, Alaska DOT was going to break cylinders as early as day 7, then day 14 and day 28 for the concrete strength development. It was expected by the contractor the concrete would be proper for post-tensioning work at about day 7. We required DOT to test at least three specimens at early ages of day 1, day 3 and day 7 in order to estimate the early strength by the maturity method. A specified number of cylinders were cast when the concrete was placed on to compare the predicted strength by the strength-maturity method and the compressive strength by cylinder testing. All of the cylinders were cured and tested in accordance with the existing AKDOT specifications. At a specified age, when the cylinders were tested to estimate the concrete strength, the maturity development in the concrete of the pier cap would be recorded. The comparisons between the cylinder strength and the predicted strength by the established strength-maturity curves (see Figure 12) are shown in Figure 18.



(a) Bridge No. 234



(b) Bridge No. 237

Figure 18 Comparison between the maturity correlation curves
and the cylinder testing data

Both hyperbolic curve and logarithmic curve of strength-maturity relationship showed the discrepancy from the cylinder testing results. It is believed this was caused by the temperature difference in the in-situ pier cap and cylinders cured in the lab. At the same age, the concrete experienced warmer temperature will have larger maturity value and therefore higher strength. In bridge No. 234, the logarithmic correlation of strength and maturity in terms of temperature-time factor gave the most conservative prediction of strength and the prediction is the closest to the cylinder testing data.

Since Bridge No. 237 was heated for the first 3 days, the temperature in the concrete of the pier cap was much higher than that in the cylinders which were cured in the lab, the maturity developed faster in the concrete and the strength were higher than that in the cylinder at the same age. Again, the logarithmic correlation of strength-maturity (TTF) is the most conservative curve.

Therefore, the data from the laboratory cured cylinder break tests could not be used as a good estimate of the strength in the concrete members, especially in the condition of cold weather concreting when heating protection is applied to the structures.

It is recommended in the future implementation of the maturity method, additional cylinder specimens be cast when the project concrete is placed to verify the strength-maturity correlation curve in the filed. The purpose is to ensure that the correlation curves are accurate enough to estimate the in-place concrete strength and to include the slight modifications in the concrete mixes which could affect the shape of the strength-maturity curves. At least two of the cylinders should be instrumented with temperature sensors and all the cylinders should be cured both in the field and in the laboratory to investigate the effect of curing conditions on the maturity and compressive strength values. Comparison of the compressive strengths of these cylinders at specified ages with the strength- maturity correlation could be used to verify and refine the strength-maturity correlation curve established from the laboratory cylinder testing. By the way, the ASTM specifications require curing under laboratory conditions only.

6 SUMMARY OF FINDINGS AND RECOMMENDATIONS

This investigation of the maturity method showed the following:

1) It is important to strictly control the maturity method procedure, including laboratory measurement of the maturity constants, generating and verifying the correlation curve, and acquiring the in-situ temperature data.

2) The maturity method provides a more realistic estimation of strength development than separately cast cylinder specimens. Application of maturity method often allows earlier subsequent construction activities and consequently project schedule could be accelerated which will result in cost-savings.

3) Both temperature-time factor (TTF) and equivalent age at a specified temperature could be easily developed of the recorded temperature history by a spreadsheet or a maturity meter. For a specified mix, either TTF or the equivalent age method in conjunction with the hyperbolic or logarithmic prediction equations may produce the most accurate strength estimates.

4) The method may be used on large projects where the time and expense of conducting the calibration and verification is justified. The method may also be useful on small projects in which the correlation curve for the concrete mixture already exists.

5) Laboratory and field testing protocols for the use of the maturity method in AKDOT&PF's concrete projects were developed (Appendix C).

6) A continuous of this work is imperative in order to make conclusive recommendations. In future study, it is recommended to verify and refine the strength-maturity relationship with field- and lab- cured cylinders, to evaluate field vs. standard cured concrete cylinders and compare these to the in-place estimates of concrete strength. The reliability and potential benefit of using the concrete maturity method in very cold

weather, which presents particular challenges for concrete construction, will be discussed. The confidence level of using maturity method for quality control and quality assurance will be assessed.

7) Limitations of the maturity method. At first, the method assumes that sufficient moisture is available during cement hydration and, therefore, any variation in strength due to poor curing during construction would not be reflected in the maturity curve. Secondly, the accuracy of the maturity curve to estimate strength of the mix during construction depends on the mix design of the in-situ concrete being consistent with the mix design used in the development of the maturity curve. The minimal change within acceptable tolerance may be allowed. Finally, the maturity method does not take into account any errors in placing and consolidation; thus, good construction practices are essential, as with any project. Each of these issues could be easily addressed through good project quality control and should not serve as an obstacle to applying maturity technology.

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Appendix A

Concrete Mix Designs – Provided by AKDOT

1. University Redi Mix: Mix # 34401A

University Redi Mix Concrete Products
3440IA Mix Design

Job #2007-027
April 2, 2007

Recommended Concrete Mix Design
Mix # 3440IA (SI Units)

Concrete F'c = 27.6 MPa in 28 days w/Type I/II Cement
Concrete F'cr = 31.5 MPa in 28 days w/Type I/II Cement

Maximum Nominal Size Aggregate (mm)	19
Cementitious Materials (kg/m³)	335
Water/Cement Ratio (kg/kg)	0.40
Entrained Air (%)	4 - 7
Slump (mm) / After HRWR (mm)	100 / 200
Sand Content (% by Volume)	42.3
Coarse Aggregate Specific Gravity (SSD)	2660
Fine Aggregate Specific Gravity (SSD)	2680

Ba:.:n Weights in Kilograms
C:ne Cubic Meter

Ingredient	Weight (kg)	Volume (m³)
Cement	335	0.1062
Water	134	0.1338
Sand (SSD)	793	0.2961
Gravel (SSD)	1074	0.4039
Micro-Air (6%)	– 98 ml / 100kg	0.0600
Polyheed 997	-- 975 ml / 100kg	
Glenium	780 ml / 100 kg	
Totals	2335	1.000

Micro-Air = Air Entraining Agent (M: .:ders product) meets ASTM C260

Polyheed 997 = Mid Range Water F ;j Agent (Master Builders product) meets ASTM C494 Type A & F

Glenium = High Range Water Redu ·:ter Builders product) meets ASTM C494 Type A & F

The Concrete Mix design Batch we :ommended are based on SSD Aggregates and they must be adjusted to meet existing m :onditions at the plant.

Appendix A – continued

2. University Redi Mix: Mix # 34501AA

University Redi Mix Concrete Products Job #2006-044
3450IAA Mix Design April 27, 2006

Recommended Concrete Mix Design
Mix # 3450IAA (SI Units)

Concrete F'c = 34.5 MPa in 28 Days W/Type I/II Cement
Concrete F'cr = 38.4 MPa in 28 Days W/Type I/II Cement

Maximum Nominal Size Aggregate (mm)	19
Cementitious Materials (kg/m^3)	390
Water/Cement Ratio (kg/kg)	0.35
Entrained Air (%)	5 - 8
Slump (mm)	25 - 75
Sand Content (% by Volume)	40.5
Coarse SPG (SSD) / Absorption	2660 / 1.2%
Fine SPG (SSD) / Absorption	2680 / 0.5%

Batch Weights in Kilograms
One Cubic Meter

Ingredient	Weight (kg)	Volume (m^3)
Cement	390	0.1239
Water	137	0.1366
Sand (SSD)	737	0.2752
Gravel (SSD)	1075	0.4043
Micro-Air (6%)	8 – 98 ml / 100kg	0.0600
Polyheed 997	195 – 975 ml / 100kg	
Totals	2339	1.000

Micro-Air = Air Entraining Agent (Master Builders product) meets ASTM C260

Polyheed 997 = Water Reducing Agent (Master Builders product) meets ASTM C494 Type A & F
(Type A = Mid Range & Type F = High Range Water Reducer [HRWR])

The Concrete Mix design Batch weights recommended are based on SSD Aggregates and they must be adjusted to meet existing moisture conditions at the plant.

Appendix A – continued

3. Fairbanks Sand & Gravel: Mix # 1601

Fairbanks Sand & Gravel
1601 Mix Design

Job #2006-085
May 16, 2006

Recommended Concrete Mix Design
Mix # 1601 (SI Units)

Concrete F'c = 27.6 MPa in 28 Days W/Type I/II Cement
Concrete F'cr = 32.1 MPa in 28 Days W/Type I/II Cement

Maximum Nominal Size Aggregate (mm)	19
Cementitious Materials (kg/m^3)	335
Water/Cement Ratio (kg/kg)	0.40
Entrained Air (%)	4 - 7
Slump (mm)	100
Sand Content (% by Volume)	39
Coarse Aggregate Specific Gravity (SSD)	2670 / 0.8
Fine Aggregate Specific Gravity (SSD)	2690 / 0.4

Batch Weights in Kilograms
One Cubic Meter

Ingredient	Weight (kg)	Volume (m^3)
Cement	335	0.1062
Water	134	0.1338
Sand (SSD)	734	0.2730
Gravel (SSD) (88% 3/4" agg; 12% 3/8" agg)	1139	0.4270
Micro-Air (6%)	8 – 98 ml / 100kg	0.0600
Polyheed 997	195 – 975 ml / 100kg	
Totals	2362	1.000

Micro-Air = Air Entraining Agent (Master Builders product) meets ASTM C260

Polyheed 997 = Mid Range Water Reducing Agent (Master Builders product) meets ASTM C494 Type A & F

The Concrete Mix design Batch weights recommended are based on SSD Aggregates and they must be adjusted to meet existing moisture conditions at the plant.

Appendix A – continued

4. Fairbanks Sand & Gravel: Mix # 1551

Fairbanks Sand & Gravel
1551 Mix Design

Job #2006-200
July 31, 2006

Recommended Concrete Mix Design
Mix # 1551 (SI Units)

Concrete F'c = 27.6 MPa in 28 Days w/Type I/II Cement
Concrete F'cr = 32.1 MPa in 28 Days w/Type I/II Cement

Maximum Nominal Size Aggregate (mm)	19
Cementitious Materials (kg/m^3)	307
Water/Cement Ratio (kg/kg)	0.43
Entrained Air (%)	4 - 7
Slump (mm)	100
Sand Content (% by Volume)	38
Coarse Aggregate Specific Gravity (SSD)	2670
Fine Aggregate Specific Gravity (SSD)	2660

Batch Weights in Kilograms
One Cubic Meter

Ingredient	Weight (kg)	Volume (m^3)
Cement	307	0.0974
Water	132	0.1319
Sand (SSD)	809	0.3042
Gravel (SSD) (84% 3/4" agg; 16% 3/8" agg)	1098	0.4115
Micro-Air (5.5%)	8 – 98 ml / 100kg	0.0550
Polyheed 997	195 – 975 ml / 100kg	
Totals	2346	1.000

Micro-Air = Air Entraining Agent (Master Builders product) meets ASTM C260

Polyheed 997 = Mid Range Water Reducing Agent (Master Builders product) meets ASTM C494 Type A (water-reducing) & F (high range water-reducing)

The Concrete Mix design Batch weights recommended are based on SSD Aggregates and they must be adjusted to meet existing moisture conditions at the plant.

Appendix A – continued

5. H. C. Redi Mix: Mix # 60341

HC Redi Mix
6.0 Sack Type I/II Cement Size #67 Mix Design

Job #2007-008
February 12, 2007

Recommended Concrete Mix Design
Mix # 60341 (SI Units)

Concrete F'c = 28 MPa in 28 Days w/Type I/II Cement
Concrete F'cr = 32 MPa in 28 Days w/Type I/II Cement

Maximum Nominal Size Aggregate (mm)	19
Cementitious Materials (kg/m³)	335
Water/Cement Ratio (kg/kg)	0.40
Entrained Air (%)	4 - 7
Slump (mm)	100
Sand Content (% by Volume)	40
Coarse Aggregate Specific Gravity (SSD)	2660
Fine Aggregate Specific Gravity (SSD)	2680

Batch Weights in Kilograms
One Cubic Meter

Ingredient	Weight (kg)	Volume (m³)
Cement	335	0.1062
Water	131	0.1305
Sand (SSD)	753	0.2833
Gravel (SSD)	1138	0.4250
Micro-Air (5.5%)	8 – 98 ml / 100kg	0.0550
Polyheed 997	195 – 975 ml / 100kg	
Totals	2357	1.000

Micro-Air = Air Entraining Agent (Master Builders product) meets ASTM C260

Polyheed 997 = Mid Range Water Reducing Agent (Master Builders product) meets ASTM C494 Type A & F

The Concrete Mix design Batch weights recommended are based on SSD Aggregates and they must be adjusted to meet existing moisture conditions at the plant.

Appendix A – continued

6. H. C. Redi Mix: Mix # 65341

HC Redi Mix
6.5 Sack Type I/II Cement Si: #67 Mix Design

Job #2007-090
May 17, 2007

Recomm nded Concrete Mix Design
M x # 65341 (SI Units)

Concrete F'c = 3 MPa in 28 Days w/Type I/II Cement
Concrete F'cr = 3 MPa in 28 Days w/Type I/II Cement

Maximum Nominal Size Aggregat mm)	19
Cementitious Materials (kg/m³)	363
Water/Cement Ratio (kg/kg)	0.36
Entrained Air (%)	4 - 7
Slump (mm)	100
Sand Content (% by Volume)	39
Coarse SPG (SSD) / Absorption %	2720 / 0.9
Fine SPG (SSD) / Absorption %	2690 / 0.4

Bat Weights in Kilograms
One Cubic Meter

Ingredient		Weight (kg)	Volume (m³)
Cement		335	0.1151
Water		131	0.1305
Sand (SSD)		753	0.2728
Gravel (SSD)		1138	0.4266
Micro-Air (5.5%)		– 98 ml / 100kg	0.0550
Polyheed 997	1	– 975 ml / 100kg	
Totals		2357	1.000

Micro-Air = Air Entraining Agent (Mast Builders product) meets ASTM C260

Polyheed 997 = Mid Range Water Rec ng Agent (Master Builders product) meets ASTM C494
Type A & F

The Concrete Mix design Batch weigh ecommended are based on SSD Aggregates and they must be adjusted to meet existing mois e conditions at the plant.

Appendix B

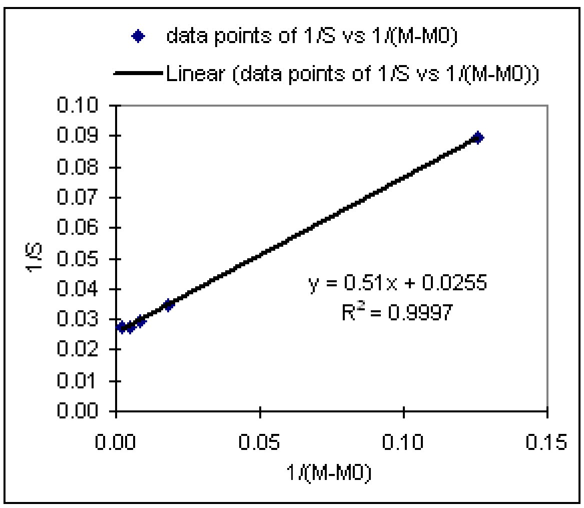
Hyperbolic Regression Analysis

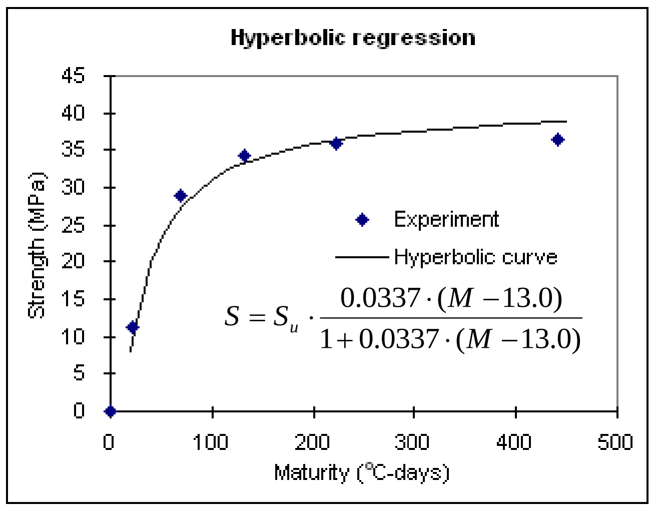
Inputs		
Age (days)	Maturity, M (deg-days)	Strength, S (MPa)
0.0	0	0.000
1.0	20.97	11.167
3.9	68.81	28.836
7.9	132.44	34.172
14.0	222.29	36.016
28.0	440.39	36.450

Procedure		
M-M_0	$1/(M$-$M_0)$	$1/S$
7.970	0.12547	0.08955
55.810	0.01792	0.03468
119.440	0.00837	0.02926
209.290	0.00478	0.02777
427.390	0.00234	0.02743

Regression Analysis	
intercept, $1/S_u$ =	0.0241
slope, $1/(S_u \cdot K)$ =	0.7147
S_u =	41.494
K =	0.0337
M_0=	**13**

M_0 is a regression constant analogous to the maturity when strength gain starts.
Assume M_0 and move the scroll bar to get the best fit straight line, by checking the R^2 value in the following chart, of 1/S vs. $1/(M$-$M_0)$.





$$\frac{1}{S} = \frac{1}{S_u K}\frac{1}{M - M_0} + \frac{1}{S_u} \quad \Longrightarrow \quad S = S_u \cdot \frac{K \cdot (M\text{-}M_O)}{1+K \cdot (M\text{-}M_O)}$$

Appendix C

PROCEDURE FOR ESTIMATING EARLY-AGE STRENGTHS OF CONCRETE BY THE MATURITY METHOD

This is a draft standard for Alaska Department of Transportation and Public Facilities

1. Scope

1.1 This procedure covers the maturity method for estimating the early-age strength of concrete. The maturity method uses the in-place internal concrete temperature over a period of time to estimate the in-place concrete strength for pavement or structural applications.

1.2 This procedure is based on ASTM C1074 "Estimating Concrete Strength by the Maturity Method". It is a three step procedure.

(a) Development of strength-maturity correlation curve

(b) Monitoring the maturity of the in-place concrete and estimate of concrete strength, and

(c) Regular validation of the strength-maturity relationship.

The contractor may use ASTM C1074 in accordance with this specification to estimate the compressive strength of the in-place concrete.

1.3 Maturity testing is an alternative to compressive strength tests for administering timing of job control functions such as ending the curing period or cold-weather protection periods, opening to service, or removal of forms or false work.

2. The Maturity Functions

The maturity shall be defined by the following functions:

2.1 *Temperature-Time Factor (TTF)*

$$M(t) = \sum (T_a - T_0)\Delta t \qquad (1)$$

Where,
$M(t) =$ Maturity index or known as temperature-time factor (TTF) (^{o}C-days or ^{o}C-hours),
Δt = Time interval, (days or hours),
$T_a =$ Average concrete temperature during time interval of Δt (^{o}C) and
$T_0 =$ Datum temperature (^{o}C)

2.2 *Equivalent Age (EqA)*

$$t_e = \sum e^{-Q\left(\frac{1}{273+T_a}-\frac{1}{273+T_s}\right)} \Delta t \quad (2)$$

Where,

t_e = Equivalent age at a specified temperature of T_s (days or hours),

Q = Apparent activation energy, or activation energy divided by universal gas constant (8.3144 J/(mol·K)) (^oK),

T_a = Average concrete temperature during time interval of Δt (^oC),

T_s = Specified temperature (^oC) and

Δt = Time interval (days or hours).

2.3 Either temperature-time function (TTF) or Equivalent Age (EqA) at a specified temperature could be used as the maturity index. Values of 0° C (32° F) or 5000 Kelvin may be used for datum temperature, T_0, or activation energy divided by the gas constant, Q, respectively unless a more accurate mix-specific value is determined per Annex A1 of ASTM C 1074.

3. Apparatus

3.1 *Cylinder Compressive Testing.* Equipments and facilities for cast, cure and testing cylindrical specimens are needed.

3.2 *Concrete Maturity Meter***.** Concrete maturity meter automatically measures, records, and displays the maturity value. Commercial meters use specific values of datum temperature or activation energy in evaluating the maturity; thus the displayed maturity index may not be the same for different brands and types of maturity meters.

3.3 *Temperature Sensors.* Thermocouple wires are required to be used with the concrete maturity meters for monitoring and recording the concrete temperature.

3.4 *System Calibration.* The system used for monitoring the temperature and maturity of concrete shall be calibrated as per the manufacturer's instructions.

4. Development of Strength-Maturity Relationship

The contractor shall develop the strength maturity relationship prior to placing any concrete on the project, and shall notify the engineer prior to development of the maturity curve.

4.1 *Preparing Test Specimens.* When the strength-maturity relationship is developed, compressive strength specimens shall be fabricated, cured and tested using the same mixture proportions and constituents of the concrete as those of the job concrete whose strength will be estimated using this practice.

(a) For every concrete design that will be evaluated by the maturity method, prepare a minimum of 17 cylinders according to ASTM C 192 “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory” or AASHTO T-22, “Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens.” Additional specimens should be cast to avoid having to repeat the procedure if there are defective specimens (See Section 4.2a). The minimum size of each batch shall be approximately 3 m^3 (or 3 $yard^3$).

(b) Perform fresh concrete testing as required by the standard specifications and record the data. Determine the plastic properties of the batch by performing slump, air content, unit weight and concrete temperature before making the strength specimens. Ensure that personnel performing these tests are ACI certified as Concrete Field Testing Technicians, Grade I or better.

(c) Embed one thermocouple into the fresh concrete of each of two cylinders. Take care to insure that the thermocouples are within 50 to 100mm of any surface and that the thermocouple wires are accessible outside the cylinder. Attach the maturity meter and activate the thermocouple immediately. Continuously read and store the data. Do not disconnect the meter unless the thermocouple has the capability of continuously recording data without an attached meter.

(d) Ensure that personnel making and testing cylinders for compressive strength are ACI certified as Concrete Field Testing Technicians, Grade I or better.

4.2. *Compressive Testing of Specimens*. Perform compression test at ages of 1, 3, 7, 14, and 28 days. Additional specimens can be made and tested at other ages to help define the strength-maturity curve.

(a) Test three cylinders at each interval. Calculate the average compressive strength of the three cylinders. Record the individual and average compressive strengths. Record the individual and average maturity values at the time of each test. Discard the cylinder result which is obviously defective. If two or more of the three cylinder are defective, evaluate a new batch unless additional cylinders are available. The specimens with the embedded thermocouples may not be tested or tested last as needed.

(b) At each test age, use the maturity meter to automatically compute and display the concrete maturity index in terms of TTF or EqA.

(c) Plot the measured strength against the corresponding values of maturity at different ages. Use a computer program to determine strength-maturity relationship through the data points. The most commonly used functions to best fit the strength-maturity relationship are logarithmic or hyperbolic functions.

4.3 *Acceptance of a Strength-Maturity Curve*. Submit a hardcopy of the strength-maturity curve; mix design and material sources; plastic concrete test results; concrete strength test results; maturity curve data with calculations and method used for monitoring maturity in the laboratory to the Project Engineer, the Regional Materials Engineer or the Construction Division.

5. Estimation of in-Place Concrete Strength

Use of maturity to estimate concrete strength is acceptable if the concrete uses the same aggregates, cementitious and admixture materials; mix design; and mixing technique as the concrete tested to develop the maturity curve. Any changes in the mix design, its components, or proportions may require that a new strength-maturity relationship be developed. Curing of the field placed concrete shall be maintained as per standard specifications.

5.1 *Placement of the temperature sensors.* For pavement and pavement repairs, temperature sensors shall be embedded at approximately mid-depth and 18 inches (450 mm) from the edge of pavement. For other applications, temperature sensors shall be embedded in locations considered critical in terms of exposure conditions and structural requirements. The thermocouple wiring may be connected to reinforcing steel or a substitute wooden dowel if steel rebar are unavailable, but the probe ending of the sensor may not be in direct contact with the reinforcing steel or formwork. The Engineer-in-Charge or Director, Materials Division may direct the location and time of installation of the thermocouples.

5.2 *Measurement of Maturity*. As soon as possible after placement of the concrete, connect and activate the maturity meter. Use the same type commercial maturity instrument as used in Section 4.1c to monitor field placed concrete. Use the same value for datum temperature or activation energy that was used to develop the maturity curve.

5.3 *Implementation.* The monitored maturity value (the required opening maturity value) in the structure could be used to estimate the concrete strength in accordance to the strength-maturity relationship to check whether the strength has met or exceeded the required strength for the specified operations, such as termination of heating protection in cold weather, form removal or application of construction loading. Clip all wires flush with the concrete surface when the maturity meter is disconnected.

5.4 *Documentation.* Maintain a separate log for each sensor which includes a unique ID; location; date and time of installation; date and time that the sensor began monitoring maturity; dates and times of all readings taken from the sensor; the corresponding temperature, maturity, and concrete age at each reading; and the date when readings were discontinued.

6. Verification of the Strength-Maturity Relationship.

Perform a strength-maturity curve verification weekly to determine if concrete strength is being represented by the current maturity curve, especially when maturity is used to estimate strength for removal of structurally-critical formwork or false work, or for steel stressing or other safety-critical operations.

6.1 *Documentation for Validation*. The contractor shall document the air, slump, and water content from the batch of concrete tested and any deviations from the original job mix.

6.2 *Specimens for Validation*. During placement of the field concrete, a minimum of four compressive strength cylinders shall be fabricated and cured using the same procedure and manner as used to develop the current maturity curve per Section 4.1.

6.3 *Sensors for Validation Specimens*. Thermocouples should be embedded within two specimens and connected to maturity meter in the manner of Section 4.1c.

6.4 *Test Specimens for Validation*. Once the specimens, according to the temperature monitored cylinders, achieve the required maturity index which corresponds to the desired maturity for the first critical action such as opening pavement to traffic or removing formwork, three cylinders shall be tested for compressive strength.

6.5 *Strength-Maturity Relationship Validated*. Compare the average compressive strength of the three cylinders with the estimated strength determined by maturity to see if the curve is verified or not. If the actual strength is greater than the strength estimated by maturity or less than 10% below the strength estimated by maturity, then the strength-maturity relationship is verified.

6.6 *Strength-Maturity Relationship Acceptable*. If the actual compressive strength is more than 10 percent above the compressive strength as determined by the strength-maturity relationship, then a new strength-maturity relationship may be developed.

6.7 *Strength-Maturity Relationship Not Validated*. If the actual strength is more than 10% below the strength estimated by maturity, the curve is not verified and a new strength-maturity relationship may require to be developed.

7. Field Documentation

The contractor shall provide the engineer with the following information prior to taking any field action based on the strength-maturity strengths:

(a) Project number, route, county, and date tested.
(b) The lot and quantity of concrete which was tested.
(c) Sensor numbers and locations.
(d) Maturity index determined for each sensor location.
(e) Estimated strength determined for each sensor location.

7.1 *Calibration and Verification Records***.** The contractor shall record all test results for equipment calibration and verification, and shall maintain all results in an organized format.

7.2 *Availability of Test Results*. Test results shall be available to the engineer at all times.

8. Designer Note

This supplement is not intended as a stand alone specification. It is a description of the Department's methods for use of maturity testing. The Designer is responsible for either developing a plan note or using already developed proposal notes when the maturity method of determining concrete strength is going to be used.